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Late Triassic intrusive complex in the Jidong region, Jiamusi–Khanka Block, NE China: Geochemistry, zircon U–Pb ages, Lu–Hf isotopes, and implications for magma mingling and mixing

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ABSTRACT

Whole-rock major and trace element geochemistry together with zircon U–Pb ages and Lu–Hf isotope compositions are reported for a Late Triassic intrusive complex in the Jidong region, Jiamusi–Khanka Block, NE China. Zircon U–Pb dating yields ages between 211 and 208 Ma for enclaves of microgranular diorite and quartz diorite, and between 211 and 209 Ma for the host granitoids. These ages correlate with a previously established intensive Late Triassic magmatic event along the eastern Asian margin. Field observations, together with petrographic features, geochemistry, and zircon Hf isotope data, preclude simple crystal fractionation or restite unmixing as a genetic link for the various rock types within the intrusive complex. The syenogranite suite has high SiO_2 (75.5–76.3 wt.%) and low MgO (0.15–0.19 wt.%), and yields enriched LILE and LREE patterns. Most of the zircons in the syenogranites have two-stage model ages of 766 and 1461 Ma, together with positive $\varepsilon_{Hf}(t)$ values of +0.6 to +9.1. These results indicate that the granitoid magmas were generated by partial melting of Meso- to Neoproterozoic lower crust. The gabbro suite has a restricted range of SiO_2 (46.1–51.9 wt.%) together with high Mg# values (49–70) and high concentrations of Ni, Co, and Cr. Zircons from two diorite samples have single-stage Hf model ages of 557–787 Ma and $\varepsilon_{Hf}(t)$ values of +1.9 to +8.3 that are consistent with the coeval gabbros previously studied in the Jidong region. These features, together with the observation that all the gabbros are enriched in LREE and LILE, suggest that the mafic magmas were derived from melting of depleted Neoproterozoic lithospheric mantle that had been metasomatized by slab-derived fluids. It is concluded that the dominant igneous suites within the Late Triassic intrusive complex formed by mingling/mixing of felsic and mafic magmas. The geochemical data, combined with regional geological investigations, indicate that the Late Triassic intrusive complex formed during lithospheric extension caused by slab break-off of the Yuejinshan oceanic plate that was subducting westward beneath the Jiamusi–Khanka Block.

1. Introduction

Suites can be defined as individual bodies of intrusive rocks within a complex that share similar petrographic and compositional features (e.g., White and Chappell, 1983). They may also represent groups of plutons that possess characteristic features that result from their derivation from source materials of a specific composition, or a limited range of composition, which differ from the source rocks (e.g., Chappell, 1996). Geochemical variations within suites have been ascribed to processes such as assimilation, fractional crystallization, magma mingling/mixing and varying degrees of partial-melt extraction from restite or unmelted source material (Chappell, 1996). Among these, magma mingling/mixing of siliceous crust and mantle-derived mafic magmas has become popular. During the past two decades, coeval associations between mafic and felsic volcanic and plutonic rocks, and their links to magma mingling/mixing phenomena, have been widely recognized from whole-rock geochemistry and Nd and Sr isotope studies (e.g., Bonin, 2004; Holden et al., 1987; Kepezhinskas et al., 1997; Qin et al., 2009; Yang et al., 2004, 2007; Yu et al., 2013; Zhang et al., 2010). Recognition of the sources of mafic and felsic magmas is one of the principal methods of identifying the occurrence of magma mingling/mixing. However, identifying specific source materials that contribute to the origin of an intrusive complex has long been a problem, as both mingling/mixing and wall-rock assimilation can modify the chemistry of magmas and result in variable Nd and Sr isotopic compositions. Recent studies have shown that zircon Lu–Hf isotopes can provide information on the nature of magma sources and the role of magma mingling/mixing processes in the generation of intrusive complexes (Kemp and Hawkesworth, 2006; Qin et al., 2009; Yang et al., 2007). This is because

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(1) zircon is resistant to later physical and chemical geological processes and can survive post-crystallization thermal disturbances (Kinny and Maas, 2003; Qin et al., 2009; Yang et al., 2007), and (2) the Lu–Hf isotopic system can track the history of chemical differentiation of the Earth (crust and mantle), as the fractionation of Lu from Hf occurs during magma generation (Kinny and Maas, 2003).

The coexistence of contrasting magma types that have been attributed to magma mingling/mixing processes has been suggested from several lines of evidence: (1) the ubiquitous presence of microgranular enclaves in igneous suites (e.g., Qin et al., 2009; Vernon, 1984; Yang et al., 2007; Yu et al., 2013; Zhang et al., 2010); (2) the existence of dendritic plagioclase crystals, acicular apatite, and blade-like biotite (Vernon, 1990); (3) linear arrays in binary diagrams that join the compositions of putative end-member magmas (e.g., Castro et al., 1991); and (4) correlations of radiogenic isotope systematics among different rocks in a suite (e.g., Dickin, 1995). Nevertheless, most of these arguments are equivocal. For example, although the presence of microgranular enclaves in granitoid rocks may serve as a tool for understanding the interactions between mafic and felsic magmas, there are still considerable discrepancies between the various models proposed to explain the origin of microgranular enclaves. The main unknowns include (1) the origin of restites (Chappell et al., 2000; Chen et al., 1989), (2) the occurrence of xenoliths of mafic mantle-derived magmas in granitoid rocks (Bonin, 2004; Vernon, 1984, 1990; Yang et al., 2004, 2006a), and (3) the nature of lower crustal mafic rocks (Kepezhinskas et al., 1997). In addition to magma mingling/mixing, the presence of linear geochemical trends can arise from other petrogenetic scenarios (e.g., DePaolo, 1981). Although radiogenic isotopes are sensitive indicators of open-system behavior, some variation can be attributed to the melting of isotopically heterogeneous sources (e.g., Gerdes, 2001) or to crustal contamination (e.g., DePaolo, 1981).

These uncertainties indicate that processes of magma mingling/mixing cannot be evaluated based on geochemical grounds alone. Field observations and petrographic evidence of mineral disequilibrium textures need to be combined with zircon U–Pb and Lu–Hf isotopic compositions and whole-rock geochemistry (Janoušek et al., 2003; Vernon, 1990). The mechanisms of magma mingling/mixing may only be understood where sequential stages of the processes can be observed. Consequently, the selection of an appropriate case study is of prime importance.

In this paper we report zircon U–Pb ages and Lu–Hf isotopic data, together with whole-rock geochemistry and petrological observations, for a Late Triassic intrusive complex from the Jidong region in the Jiamusi–Khanka Block, NE China. In this complex the effects of various stages of magma mingling and mixing can be observed in detail. These new data provide insights into the origin of the intrusive complex and yield important information on the early Mesozoic tectonic evolution of northeastern China.

2. Geological setting

The Central Asian Orogenic Belt (CAOB) (Eizenhöfer et al., 2014; Jahn et al., 2000) is one of the largest accretionary orogens on Earth (Sengör et al., 1993; Windley et al., 2007; Fig. 1a) and considered to have evolved over a period of some 800 million years, from the latest Mesoproterozoic to the late Paleozoic, through accretion of ophiolites, arc/backarc systems, and microcontinental fragments (Safonova et al., 2011; Windley et al., 2007; Yarmolyuk et al., 2012). The NE part of China and adjacent regions are considered as the eastern segment of the CAOB (Fig. 1b), which is a collage of several microcontinents, including, from southeast to northwest, the Jiamusi–Khanka, Songliao, Xing'an, and Erguna blocks (Jahn et al., 2000; Sengör et al., 1993; Yu et al., 2014; Fig. 1b). It has previously been suggested that this segment of the CAOB has undergone two stages of evolution under different tectonic regimes (Wu et al., 2002): (1) the formation of multi-arc systems and accretionary complexes due to the subduction of the Paleo-Asian oceanic slab and subsequent consolidation of multiple fragments during pre-Mesozoic times (Lehmann et al., 2010; Safonova et al., 2009; Windley et al., 2007); and (2) the reactivation of the orogenic belt responding to the subduction of the Paleo-Pacific oceanic plate (Dong et al., 2014; Wu et al., 2002) or mantle plume activities (Safonova et al., 2009; Yarmolyuk et al., 2012) during Mesozoic and Cenozoic times. The Jiamusi–Khanka Block is regarded as the southern extension of the Bureya Massif of the Russian Far East, located in the easternmost part of NE China (Fig. 1b). Traditionally, it was believed that the Jiamusi–Khanka Block was part of the CAOB (HBGMR, 1993; Meng et al., 2010; Zhou et al., 2010a). However, based on the occurrence of ~500 Ma metamorphic events and ~530 Ma granitic plutons in Prydz Bay, East Antarctica, and in South Australia, Wilde et al. (1997) suggested that the Jiamusi–Khanka Block was part of Gondwana. More recent studies by Wu et al. (2011) and Yang et al. (2014a) support a model whereby the Jiamusi–Khanka Block is an exotic Gondwana fragment. Yang et al. (2014a) further proposed that the Jiamusi–Khanka Block rifted away from Gondwana and drifted northward in the Early Permian–Late Triassic to a location isolated from the CAOB and facing the Farallon Plate.

In the easternmost part of NE China, the Jiamusi–Khanka Block is bounded to the east by the Nadanhada Terrane and the Sikhote–Alin accretionary complex belt, to the northwest by the Mongolia–Okhotsk suture zone, and to the west by the Songliao terrane (Fig. 1b). The Jiamusi–Khanka Block comprises three complexes: (1) the Mashan Complex, (2) the Heilongjiang Complex, and (3) various stages of igneous complexes. The Mashan Complex (previously the 'Mashan Group' in the Chinese literature) is a predominantly granulite-facies terrane that records peak metamorphism at ~500 Ma (Wilde et al., 1997, 2000). The Heilongjiang Complex (previously the 'Heilongjiang Group' in the Chinese literature), which occurs only in the western part of the Jiamusi–Khanka Block, is a blueschist-facies terrane that is structurally interleaved with the Mashan Complex (Wu et al., 2007). The Heilongjiang Complex is believed to represent an accretionary mélange that hosts a major crustal suture zone along which the Jiamusi–Khanka Block collided with the Songliao Block in response to subduction of the Pacific Ocean crust at ca. 185 Ma (Wu et al., 2007; Zhou et al., 2009).

The granitic rocks of the Jiamusi–Khanka Block were emplaced during three major stages: Cambrian (530–493 Ma), Permian (299–254 Ma), and Late Triassic (223–212 Ma) (Bi et al., 2014; Wu et al., 2011; Yang et al., 2012, 2014a,b). These Phanerozoic granitoids, together with widespread volcanic rocks, make up much of this block. The Khanka Block occurs mainly in Far East Russia with only a small segment cropping out in NE China. The metamorphic rocks of the Russian part of the Khanka Block yield an age for the protolith of 757 ± 4 Ma, and the age of peak metamorphism is 506.9 ± 2.6 Ma (Khanchuk et al., 2010).

The present study was carried out in the Jidong region of eastern Heilongjiang Province, southeastern Jiamusi–Khanka Block (Fig. 1c), where exposed strata include the Precambrian Heilongjiang "Group" and the Permian Pingyangzhen, Dongzigou, and Yanggang formations (HBGMR, 1993). The Heilongjiang "Group" consists of Precambrian basement composed of greenschist, marble, quartz schist, and two-mica schist (HBGMR, 1993; Zhou et al., 2009; Yang et al., 2014b), whereas the Permian strata are composed of arc-related volcanics (basalt–andesite–rhyolite) associated with minor siltstone and shale (HBGMR, 1993). In addition, Mesozoic to Cenozoic volcanic–sedimentary assemblages, along with early Paleozoic to Early Triassic intrusive rocks, are widely distributed in the region (Fig. 1c; HBGMR, 1993; Meng et al., 2008; Yang et al., 2014a,b).

3. Field relations and sample descriptions

According to field and petrographic observations, the Late Triassic intrusive complex within the Jidong region in the Jiamusi–Khanka Block can be divided into five different groups (Fig. 1c): Group 1 is a gabbro suite, Group 2 is a gabbro-diorite suite, Group 3 is a microgranular enclave suite composed of intermediate rocks, Group 4